

THE CARBON CHEMISTRY OF METEORITES: RELATIONSHIPS TO COMETS
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The carbonaceous meteorites exhibiting extensive alteration by liquid water bear a strong relationship to comets. Not only is their elemental composition closer to solar in relative abundances than other meteorites, they are water rich; and they contain isotopic compositions among refractory and volatile elements indicative of presolar components. Some of these isotopic anomalies occur in organic compounds and carbonaceous grains signifying the presence of discrete and identifiable carbon components derived from interstellar and circumstellar matter. Insofar as comets and meteorites are ultimately formed from interstellar gas and dust, and comets have been subjected to considerably less aqueous and thermal evolution than carbonaceous meteorites, the interstellar imprint should be much stronger and better preserved in comets.

The organic matter that can be extracted from carbonaceous meteorites by solvents is structurally diverse and exhibits a wide range of isotopic compositions for H, C and N. Many classes of compounds occur, ranging from simple hydrocarbons to polycyclic heteroaromatics with multiple functional groups, including aromatic hydrocarbons, aldehydes, ketones, amines, amino acids, carboxylic acids, and purines among others. The simplest homologues of several of these classes have been observed in comets and giant molecular clouds.

Among the amino acids alone, about 30 discrete stereochemical structures have been identified, and at least 20 remain unidentified. No single production mechanism [e.g., electric discharges, Fischer-Tropsch Type (FTT) synthesis, uv-irradiation, energetic ion irradiation, HCN polymerization and hydrolysis, Strecker synthesis], nor any single environment of synthesis (i.e., solar nebula, molecular cloud, parent body) has yet been able to account for the observed variation in structures and abundances. The overall diversity of the organic compounds argues strongly for multiple sources and synthesis mechanisms. This conclusion is substantiated by the wide variations observed in the isotopic compositions of H (~1500 o/oo), C (~60 o/oo), and N (~90 o/oo) contained in the extractable organics. Notably, the deuterium enrichments in the amino and carboxylic acids are attributable to incorporation of D-rich interstellar molecules during synthesis of the acids. Indicators uniquely characteristic of nebular or parent body origins are not yet apparent.

Significant abundances of organic compounds and wide variations in their molecular structures and isotopic compositions appear to be restricted to those meteorites composed of mineral assemblages resulting from extensive alteration by liquid water. This water may have been accreted directly on the parent body as water ice during a nebular condensation sequence or it may have been carried to the parent body in the form of cometesimals during accretion. The former scenario entails FTT and other disequilibrium syntheses in the nebula to account for the organic compounds, which conflicts with the observed deuterium enrichments and isotopic variations in C and N in the organic matter, as well as with the relative abundances of highly volatile simple hydrocarbons in the meteorite samples. The favored latter scenario delivers to the meteorite parent body relatively large icy reservoirs (possibly up to km in diameter) of volatile and refractory organic interstellar components

accreted elsewhere and preserved at low temperatures.

Mobilization of liquid water in carbonaceous meteorite parent bodies altered the mineralogy of pre-existing anhydrous mineral assemblages. In analogous fashion, thermally or water labile nebular species previously accreted or interstellar molecules (e.g., free radicals, cyanopolyynes, ketenes) accreted in cometary ices, would also have undergone chemical changes on the parent body when the ice melted and aqueous reactions could occur in the presence of mineral surfaces. For example, some of the amino and carboxylic acids now found in meteorites may have been formed by hydrolysis of precursive nitriles; some may have been synthesized by the Strecker route from ammonia, HCN and simple aldehydes. Analyses of returned comet nucleus samples should be conducted at temperatures no higher than those experienced by the sample during acquisition and return to Earth in order to prevent further alteration of labile compounds. In addition to the roster of known interstellar molecules, the low temperature characterization of organic compounds formed in simulations of astrophysical processing of interstellar and cometary dust and gas should provide valuable guidelines as to what may be found in comet samples.

A small fraction of meteoritic carbonaceous grains have also been implicated as interstellar in origin either by isotopic anomalies in the C, N, and Si of which they are comprised or by their contents of isotopically noble gases. These minor components include diamond, SiC, and several poorly characterized forms of elemental carbon.

The structure of the bulk of the solid carbonaceous grains, which accounts for most of the carbon in the meteorites (the so-called kerogen or polymer), is also poorly characterized. The grains are obtained as sub-micron to micron-sized clumps of smaller particles by dissolving the meteorite sample in acids. Depending on the petrologic type of carbonaceous meteorite, this solid material appears to vary in its proportions of amorphous (aliphatic) to poorly ordered turbostratic (aromatic) to highly ordered turbostratic structures. Mixed with amorphous regions are tangled ribbon-like structures with microcrystallite dimensions ranging from tens to hundreds of angstroms. This material exhibits minor variations in carbon isotopic composition, significant enrichments in N^{15} , and large enrichments in deuterium. The apparently interstellar deuterium enrichment is preserved in both aliphatic and aromatic moieties. How much of the structural and isotopic variation in this material is the result of nebular or parent body processes is unclear. Spectroscopic similarities with interstellar polycyclic aromatic hydrocarbons have been pointed out, and analogies with the CHON particles of Comet p/Halley are obvious. Similar grains with possibly higher proportions of amorphous material should occur in comets. Furthermore, one might predict that organic matter will be found intermediate in molecular weight between the solvent extractable compounds and the solid carbon phases.

Usually these carbon phases are isolated after extensive chemical treatments of bulk meteorite samples; and they are analyzed as agglomerates, largely because the individual grains are extremely small and the isolation process yields aggregates. In comets, however, they may occur dispersed among ice grains, which could allow structure and composition to be determined at the level of individual particles. Thus individual core-mantle particles and curved sheets of polycyclic aromatic structure may be found, as have been postulated for interstellar dust. Some evidence of such structures has been obtained from study of the Orgueil meteorite.